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CONDITION ASSESSMENT AND DETERIORATION PREDICTION TOOLS FOR CONCRETE BRIDGES: A NEW LOOK

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ABSTRACT

Structural problems created by corrosion, ageing, aggressive environments, material defects and unforeseen mechanical or seismic loads can compromise the serviceability and safety of bridges. The importance of an effective bridge-management system (BMS) cannot be overstated, especially in light of the recent collapse of bridges in North America and elsewhere. Several technologies are available for assessing the condition of concrete bridges and a number of deterioration models are used to predict future bridge conditions and estimate associated funding requirements. This paper critically reviews the different available condition assessment and deterioration prediction approaches for concrete bridges. The potential applications of condition assessment technologies with particular focus on their advantages and limitations are presented. The various types of deterioration models are discussed and compared. The findings indicate that: (i) non-destructive testing (NDT) methods and structural health monitoring (SHM) systems can play a major role in effectively evaluating the conditions of concrete bridges; (ii) mechanistic models for deterioration prediction embrace a reliability-based approach that can provide bridge owners and maintenance personnel with an improved tool to assess bridge conditions and to make decisions regarding their maintenance; and (iii) automated data collection and interpretation analysis is needed for improved BMS. The challenges associated with the different technologies and models are outlined. Furthermore, to empower bridge asset managers in making more informed decisions, recommendations are made on the selection of appropriate evaluation and prediction models that meet desired service goals.

Keywords: Bridge management system, bridge condition assessment, deterioration models, non-destructive testing, structure health monitoring.

1. INTRODUCTION

Existing bridges represent strategic components of infrastructural networks. Aging and deterioration of bridges can lead to structural and/or functional failure. Bridge failures can be catastrophic, both in terms of human life and economic loss, rendering the task of managing this important asset a complex endeavour that attracts growing attention. According to the Canadian infrastructure report card (2016), 26% of bridges are in fair, poor and very poor condition while as per the United States' 2013 infrastructure report card, an annual investment of $20.5 billion would be needed to eliminate the backlog of deficient bridges in the USA by year 2028. An effective bridge management system (BMS) highly depends on accurate and objective information about the condition of the bridge. Reliable assessment of the bridge health is necessary to predict the progress of deterioration, to provide the required inputs for making cost-effective maintenance, rehabilitation, and replacement decisions (MR&R), and to ensure that safety, serviceability and functionality of a bridge can be sustained over its designed service life.

Visual inspection is the default bridge inspection methodology, yet its results heavily depend on the expertise and judgment of bridge inspectors, yielding primarily qualitative and subjective decisions. Structural health monitoring (SHM) encompasses a range of methods and practices designed to assess the condition of a structure based on a combination of measurement, modeling and analysis. The SHM technology has not been widely adopted as a routine approach for bridge monitoring in Canada and the United States. However, recent improvements in the functionality and performance of SHM systems make it a viable approach for reliable and potentially real-time bridge assessment. Non-destructive evaluation (NDE) approaches enable the detection of deterioration processes at its early stages. NDE can be incorporated into the inspection process to evaluate hidden defects such as reinforcing steel corrosion or crack propagation. However, the use of NDE techniques is usually specified for special inspection when severe deficiencies are observed. A deterioration model is a link between a measure of existing bridge condition and a vector of explanatory variables that represent the factors affecting bridge deterioration (Black et al., 2005). Accurate prediction of the deterioration rate is crucial to the success of any BMS. Deterioration models can be categorized in different mechanisms. For example: (i) linear or nonlinear, (ii) deterministic or stochastic, (iii) aggregate or disaggregate, and (iv) mechanistic or empirical models. Several developed probabilistic models are widely used for predicting the performance of bridge components and networks. For instance, the Markov chain approach is a probabilistic model that has been adopted in most BMSs. The reliability-based mechanistic models are promising where quantitative performance indicators (physical parameters) can be determined through detailed condition surveys, using NDE or SHM techniques, and then applying analytical assessments to predict the micro-response of bridge components (Morcous et al., 2010). However, most of the currently implemented condition assessment and deterioration models suffer from some limitations and will be discussed in this study.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The aim of this study is to explore the condition assessment techniques and deterioration models that are currently in use by the bridge community. To achieve this goal, the following objectives are outlined: (1) delineate recent research efforts in BMS; (2) investigate the potential applications of condition assessment techniques with particular focus on their advantages and limitations; (3) discuss and compare the various types of deterioration models; (4) determine the challenges associated with each technology; and (5) assist bridge asset managers to make more informed decisions on the appropriate evaluation methods. The methodology adopted for the achievement of these objectives is based on reviewing articles within the domain of bridge asset management with attempts to capture recent relevant developments. The selected articles were evaluated to define relevant categories and classify the articles in the defined categories. The technologies were then compared to identify their key application areas, principal strengths and limitations. The challenges and technology gaps that need further research were addressed and hence, guidelines to the bridge community for the selection of appropriate technologies were recommended.

3. BRIDGE INSPECTION AND CONDITION ASSESSMENT

The condition assessment of an existing bridge aims at assessing whether it will function safely over a specified residual service life. The most significant challenge to bridge condition assessment is the quantification of information on bridge condition by development of technologies for objective and accurate condition assessment and reliability evaluation. Current bridge condition assessment methods are categorized in Figure 1.

3.1 Visual Inspection

Guidelines for visual inspection (VI) of existing bridges have been developed in many countries. The National Bridge Inspection Standards (NBIS) is the governing document in the USA. VI is often conducted within 24-month intervals depending on the condition of the bridge. Similarly, the Ontario Structures Inspection Manual (OSIM) describes procedures for carrying out detailed VI of material defects, performance deficiencies and maintenance needs of bridges. Emergency detailed inspection should be carried out immediately when a component contributing to the overall bridge stability has failed, or in case of imminent failure, or when public safety is at risk. The use of bridge inspection reporting software has been explored by several asset management software developers. A bridge inspection software typically consists of interactive forms that retrieve customized inspection guidelines and relevant historic bridge inspection data, capture bridge evaluation data, and automatically associate the captured information with the bridge components, making the bridge inspection documentation intuitive (Akula et al., 2014). Research results indicate that assessing a bridge condition by VI is unreliable, being unable to identify correctly the repair priorities. The quality and consistency of visual inspection results greatly depend on the motivation, qualification and equipment of those conducting such inspections. However, although VI is subjective and qualitative, it is likely to remain the most significant aid for bridge condition assessment.

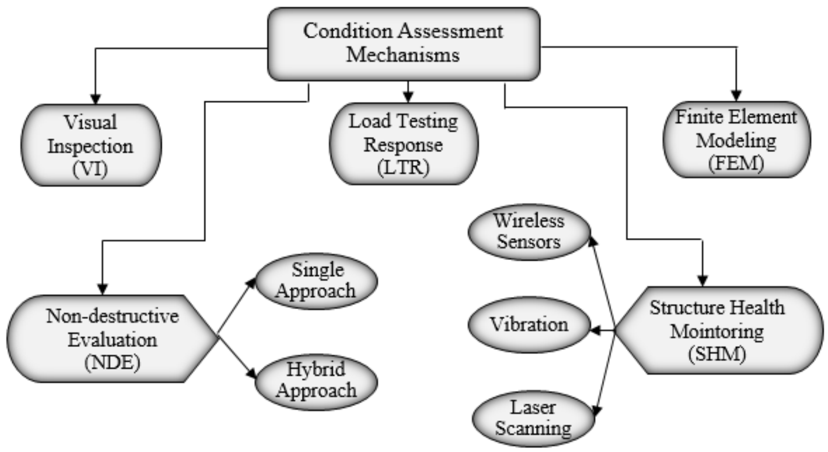

Figure 1: Condition assessment mechanisms for concrete bridges.

3.2 Load Testing Response (LTR)

Not only do older bridges deteriorate overtime, but may also not have been designed for increased load demand. The reliability bridge evaluation rating process described in the AASHTO's manual is based on load testing response. Load testing is a procedure to determine the safe loading levels of a bridge, leading to a load rating which provides the capacity level of a bridge. Through forced static and dynamic load testing in varied load patterns, the maximum response can be detected using strain transducers placed at critical locations on the bridge. The load ratings can be determined by allowable stress, load factor, or load and resistance factor methods. Bridge ratings performed by all three methods follow similar basic procedure, differing primarily in the load or resistance factors in the rating equation. Although, the ratings are determined in both inventory and operating load levels, these three competing rating methods may yield different rated capacities for the same bridge (Wang et al., 2011). Another useful procedure is the use of B-WIM (bridge-weight in motion) monitoring data to evaluate the bridge condition for enforcement and safety assessment, especially for bridges under load restriction due to distress. Bridge structural integrity can also be assessed by the most probable values of the structural element properties, such as the stiffness obtained using vibration measurements and video traffic recording. Wang et al., (2011) recommended guidelines for reliable evaluation of existing bridges. These guidelines are established by a coordinated load testing program and advanced computational modeling integrated within a structural reliability framework to determine practical bridge rating methods. However, loads experienced by bridges are often inferred from limited measurements of external conditions (i.e. ambient temperature, wind speed/direction, wave heights). Therefore, the monitoring of load testing can be combined with other technologies such as SHM methods for improved assessment of concrete bridges.

3.3 Non-Destructive Evaluation (NDE)

Non-destructive evaluation (NDE) methods enable detection of deterioration processes at their early stages and monitoring of deterioration progression through periodical surveys. NDE approaches can be incorporated into the inspection process to evaluate hidden defects such as reinforcing steel corrosion and crack propagation. Condition indices obtained from NDE survey results can provide more objective and accurate condition assessment, enabling to monitor the progress of deterioration (Gucunski et al., 2014). NDE is specified in some BMSs when visual inspection results indicate irregularities within the structure. There are several NDT methods capable of evaluating and identifying different types of damage in reinforced concrete bridges and the most commonly used methods are illustrated in Figure 2. The principles and testing procedures of these methods are described in details in the American concrete institute report (ACI 228.2R-13).

3.3.1 <u>NDE Single Application</u>

Use of simple NDE tools such as chain drag (CD) and hammer sounding (HS) is the predominant practice of condition assessment of concrete bridge decks. CD and HS are low-cost methods but their result are subject to the operator's judgment and experience (Yehia et al., 2007). Each of the NDE methods uses a unique physical principal of the bridge materials to identify deterioration and its location. For example, corrosion can be evaluated by Halfcell potential (HCP), electrical resistivity (ER), and ground penetrating radar (GPR) measurements. Increased electrical conductivity due to the presence of moisture, and chloride ions leads to lower measured electrical resistivity by ER, or an increased attenuation of electromagnetic waves measured by GPR. The presence of vertical cracks leads to a reduced modulus of elasticity of concrete, which can be captured using the ultrasonic surface wave (USW) method. Delamination can be detected using impact echo (IE), and infrared thermography (IRT) tests. However, due to the composite nature of concrete and the many causes of deterioration, a diverse set of NDE technologies is required for a complete understanding of a bridge condition (Gucunski et al., 2014).

3.3.2 NDE Hybrid Application

Although single NDE approaches have their own merits, there is no single NDT technology that is capable of identifying all of the various deterioration phenomena that can affect a bridge. Bridge condition assessment results from different NDT techniques do not necessarily agree (Yehia et al., 2007). Therefore, NDT practitioners often adopt a multi-modal NDT approach which allows identificatiying different damage states, yielding a more complete understanding of a bridge condition. For instance, Gucunski et al., (2014) developed a fully autonomous robotic system named "RABIT" (Robotics Assisted Bridge Inspection Tool) for the condition assessment of concrete bridge decks using multiple NDE technologies (ER, IE, USW, and GPR). The system utilizes three high resolution cameras for crack mapping and documentation of previous repairs and to image larger areas of the deck for inventory purposes. The robot's data visualization platform facilitates an intuitive 3-D presentation of three deterioration types (rebar corrosion, delamination, and concrete degradation) and deck surface features. Pailes, (2014) developed a multi-NDT condition assessment model for concrete bridge decks. The NDT methods utilized were ER, HCP, GPR, IE, and CD. He identified the correlations between the utilized methods and developed a statistics-based approach to threshold identification for ER, HCP, and GPR, which were fused and converted into a deterioration based condition assessment that identifies locations of active corrosion, delamination, and cracking.

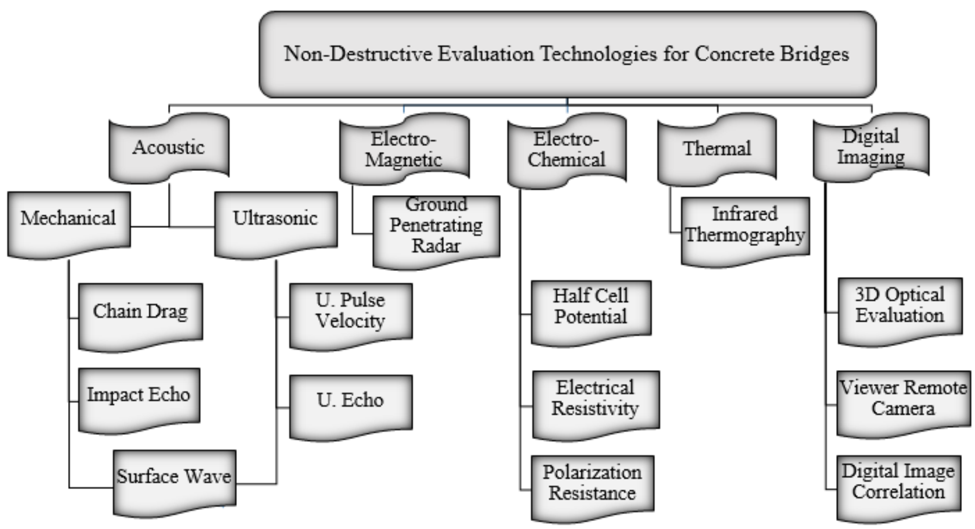

Figure 2: Nondestructive evaluation methods for concrete bridges.

3.4 Structural Health Monitoring (SHM)

Structural Health Monitoring (SHM) is a non-destructive in-situ sensing and evaluation technique that uses multiple sensors embedded in a structure to monitor and analyze the structural response and detect anomalous behavior (Bao et al., 2013). SHM applications can be deployed for short-term assessment of a specific bridge performance aspect (e.g. corrosion or scour) or for long-term monitoring to assess a wide range of bridge health conditions. Most SHM systems have similar fundamental elements: (1) measurements by sensors and instrumentation, (2) structural assessment (e.g. peak strains or modal analysis), and (3) condition assessment to support MR&R related decision-making. The functionality of an SHM system depends on the type and number of sensors used, which can be tailored to capture a various physical measurements associated with dynamic loads, environmental conditions including temperature gradients, and material parameters such as creep, shrinkage and corrosion. Agdas et al., (2015) summarized the common sensor systems and their potential purposes and measurement capabilities. For example, measuring bridge deflections requires a fixed reference point, GPS, radar systems, video, and laser-based systems.

3.4.1 Wireless Sensors

Standard strain gages and accelerometers have been in wide use to measure structural responses. More recently, fiber-optical sensors (FOS) have been applied for strain, temperature, and vibration measurement. FOS are less susceptible to electrical noise than strain gages and accelerometers and thus, can provide distributed measurements along a bridge (Agdas et al., (2015). However, the sensors mounted on bridges could not represent the complete behavior of the investigated bridge since they are discretely located. With the increased availability of wireless data networks, sustainable SHM systems have been developed so that pervasive sensor networks allow centralized data collection and more efficient monitoring of multiple bridges and bridge segments across large areas. O'Connor et al., (2014) employed a wireless sensor network to measure bridge accelerations, strains and temperatures. Limitations of using wireless sensors include constraints in power and transmission bandwidth. However, power supply from solar, vibration, or wind is required to sustain long-term wireless sensor network operations while communication bandwidth constraints can also be made less relevant when less data is conveyed (Bao et al., 2013).

3.4.2 Laser Scanning

Laser scanning capabilities have been used in recent years for several health monitoring and damage detection applications of structures. Texture mapped 3D point clouds can be used effectively to document quantitative information on present conditions of bridges. Guldur et al., (2015) developed a condition rating system of bridge components using detected and quantified surface damage from texture-mapped laser point clouds. The system provides structural evaluation, giving an overall condition of the bridge based on major deficiencies, including its ability to carry the required loads. Akula et al., (2014) introduced an integration condition assessment system through a software called *Toolkit*, which allows inspectors an intelligent interpretation of SHM obtained data and the condition assessment data corresponding to equivalent components recorded visually by other respondents. While the SHM approach is promising as an effective bridge management tool, it still needs further dedicated research to make it a simple, reliable and low-cost option.

3.5 Finite Element Modeling (FEM)

Finite-element modeling (FEM) is widely used for the condition assessment of concrete bridges. The construction process, erection methods, concrete properties, geometric accuracy, and environmental conditions are key factors in the development of robust FE models. For instance, Xia et al., (2005) developed FEM for the quantitative condition assessment of a damaged reinforced concrete bridge deck, including damage location and extent, residual stiffness evaluation, and load-carrying capacity assessment. Wang et al., (2011) developed FEM to assist the design of load tests and the interpretation of their results. The actual bridge test results, in turn, were used to validate the FE analysis and the measured bridge deflections were found in good agreement with those computed by FE analysis. Alani et al., (2013) proposed an integrated bridge health mechanism where a FEM was developed using data from visual inspections and calibrated using NDT survey results. The system identifies the portion of the bridge which had undergone the greatest amount of deterioration. Ghodoosi et al., (2015) evaluated the system reliability of concrete bridges using a FEM model and found that the estimated element-level structural conditions degrade faster once corrosion is initiated and spalling of concrete becomes evident. FEM can also be used to evaluate the reliability of bridges that use nonconventional materials or structural forms. For example, Ghodoosi et al., (2015) developed a FE condition assessment model for a restrained bridge deck system and calibrated the model with experimental results giving static deflection, vibration characteristics, load distribution, and crack patterns.

4. BRIDGE DETERIORATION MODELING

There is a variety of bridge deterioration models that have been developed and can be categorized from literature into three main categories: deterministic, stochastic, and mechanistic models. Those models and their techniques are summarized in Figure 3. Each category is briefly discussed below.

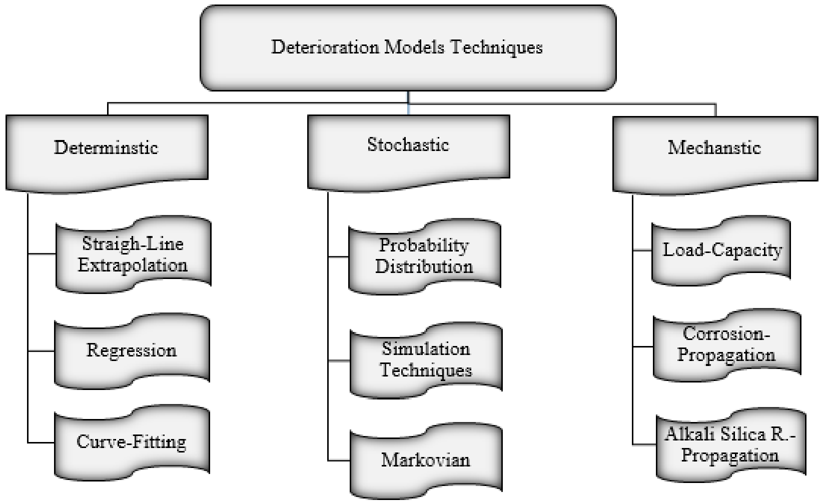

Figure 3: Deterioration models techniques.

4.1 Deterministic Models

Deterministic models use a single defined value to describe bridge elements' condition at a certain given time. They utilize historical data to estimate the deterioration rate using the available statistical techniques. Accordingly, the models can be categorized as straight-line extrapolation, regression and curve-fitting models. For instance, straight-line extrapolation models can be used to predict the material condition rating of a bridge given the assumption that traffic loading and maintenance history follow a straight line. The models require an initial condition that can be assumed at the time of construction and only one condition measurement after construction at the time of the inspection. Although, these models are accurate enough for predicting short-term conditions, they are not appropriate for conditions at long periods of time. They cannot also predict the rate of deterioration of a bridge that has undergone some repair. Regression models depend on developing an empirical relationship between two or more variables that affect the bridge condition; one dependent variable and one or more independent variables. Several forms of regression models are presented in the literature including linear and non-linear regression. Linear regression models do not provide sufficient accuracy and may underestimate or overestimate the bridge condition at a specific time while the non-linear regression models provide more adequate prediction accuracy (Morcous et al., 2010). Curve-fitting techniques are mathematical methods that depend on constructing a polynomial that best fit bridge condition data. A third order polynomial curve, based on the relationship of bridge component condition rating versus age, was found as an accurate prediction model for several concrete bridges (Elbehairy et al., 2006).

4.2 Stochastic Models

The deterioration process has a stochastic rather than a deterministic nature since several complex mechanisms characterize the variability of a deteriorated element. The use of stochastic models has contributed significantly to the field of modeling bridge deterioration due to the high uncertainty and randomness involved in the deterioration process. Generally, stochastic models can be categorized into probability distribution, simulation and Markov chains models (Morcous et al., 2010). A probability distribution describes the probabilities associated with all values of a random variable. For example, if the random variable is the condition rating of an element in a bridge, then the probabilities associated with all of its values are described by a probability distribution function rather than a deterministic value. The use of probability distribution requires knowledge of the distribution for the variables being predicted, which limits the use of this technique for individual distress prediction (Abu Dabous et al., 2008). An effective way to deal with uncertainties is through simulation, which can provide more accurate estimates using a large number of "what if" scenarios. The Monte Carlo simulation method takes both sensitivity and input variable probability distribution into consideration and have been widely utilized in concrete bridge deterioration models. The deterioration can be simulated if enough statistics on the transition times required for an element to change its condition are available. The output of the simulation is a probabilistic deterioration profile in terms of the time taken to change from one condition rating to another.

4.2.1 Markovian Models

A stochastic process is generally defined as the process in which the past behaviour influences the future ones. A Markov process is a conditional stochastic process where the transition probability from a given behaviour to a future behaviour is dependent only on the present behaviour and not on the manner in which the current behaviour was reached (Elbehairy et al., 2006). This assumption was made for simplicity and to facilitate computations but not supported by mechanistic knowledge of material behaviours (Abu Dabous et al., 2008). The Markovian models are the most common example of state-based probabilistic deterioration models and have been employed in many advanced BMSs such as Pontis, Bridgit, and OBMS. State-based probabilistic deterioration models are those used to predict the probability distribution of transition states from one condition to another over multiple discrete time intervals. The Markovian model takes advantage of the discrete condition states identified for inspections, to provide a simple way of describing the likelihood of each possible change in condition at evenly-spaced intervals. Figure 4 shows an example of how a Markovian model can describes the change in condition of a new element over time.

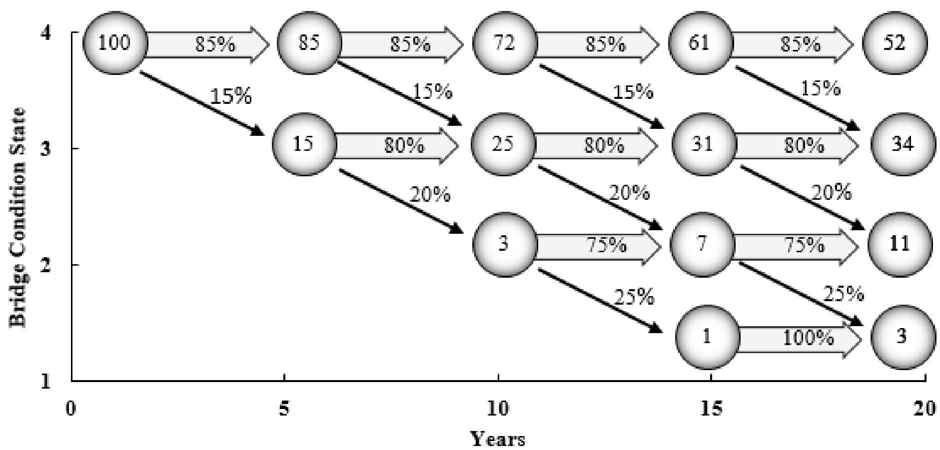

Figure 4: Example of a Markovian model.

The main challenge in Markovian models is the derivation of the transition probabilities. Several methods have been adopted to estimate the transition probabilities such as percentage prediction method, expected-value method, ordered probit model, and regression-based optimization methods. Those methods can be used when a statistically significant number of consistent and complete sets of condition data are available, otherwise Monte Carlo method or expert judgment elicitation procedure may be applied (Black et al., 2005). More improved and realistic models have been recently developed to account for the effect of the time spent between the states on the transition probabilities (i.e., Semi-Markov, Weibull Survival models, and Hybrid Markov-Weibull models) and to relax the state independence assumption by accounting for the past condition among other explanatory variables (Black et al., 2005). The Bayesian belief network (BBN) models also offer a compact representation of a joint probability distribution, together with a rigorous formalism for the construction of models relying on probabilistic knowledge. Bayesian's procedure has great advantages that cover problems of insufficient data and difficulty in estimating model parameters but it demands careful considerations for the convergence process (Nasrollahi and Washer, 2014). If condition ratings are unavailable, the backwards prediction models (BPM) can produce an estimated rating for the unavailable components or data and use time delay analysis to predict the condition ratings of future components.

4.3 Mechanistic Models

Mechanistic models describe the specific deterioration mechanisms of particular bridge components where deterioration is described by quantitative performance indicators through knowledge of the physical and chemical processes involved in the deterioration process (Lu and Liu, 2010). Modeling of bridge load-capacity, chloride-induced corrosion, and alkali-silica reaction (ASR) are some examples of research efforts towards the use of mechanistic deterioration models. For instance, Wang et al., (2011) used load-carrying capacity to predict bridge deterioration. Ian et al., (2015) modeled the deformation of concrete bridges due to the effects of ASR, creep, and shrinkage. Lu and Liu, (2010) developed an analytical model describes the mechanism of damage initiation and accumulation to predict corrosion-induced cracking, spalling, and delamination of reinforced concrete decks and performed numerical simulations, using a FEM, of the condition evolution for different values of model parameters. Morcous et al., (2010) utilized Monte Carlo simulation to generate the probability density function of the time to corrosion initiation and to capture the stochastic nature of the deterioration process. Jalalifar and Tarighat, (2014) considered the spatial variability of the deterioration parameters across the bridge components (the materials and geometrical properties) and developed a deterioration model of concrete bridges, exposed to corrosion. Shafei et al., (2014) calculate the corrosion initiation time through a detailed computational model considering the most influential parameters, including ambient temperature, relative humidity, chloride binding capacity, and exposure conditions. They also provided a detailed mechanical model, which considers the effects of corrosion on decreasing the cross-sectional area of steel, yield strength of steel and the loss of the concrete cover.

5. DISCUSSION

The process of bridge condition assessment is challenging, involving the aggregation of diverse distress indicators. Providing a suitable measure and accurate condition evaluation becomes increasingly complex due to uncertainties attributable to inherent subjectivity in the inspection and/or interpretation processes. The advantages and limitations of the commonly used condition assessment approaches of concrete bridges are summarized in Table 1. Visual inspection suffers from limitations such as the required time of inspection, the assessment subjectivity, a number of safety risks associated with field inspections, and the need for a clear line of sight to conduct condition assessment. NDE technologies can enhance accuracy and yield more efficient condition rating and makes the assessment of a large population of bridges feasible. Integrated remote sensing technologies are also gaining popularity as they provide higher evaluation details and more comprehensive defect detection. SHM is becoming common in bridge monitoring. Using wireless SHM to monitor the progression of deficiencies identified during a visual inspection allows for continuous monitoring of identified defects, while maintaining a safe use of the bridge. Yet, SHM systems have some limitations which can hinder their adoption as part of BMSs. These include system complexity which depends on the desired functionality characteristics, system maintenance to sustain long-term operation, and the requirement of automated data analysis to locate potential damages. Data collection using either NDE methods or SHM systems is the most reliable strategy to improve and update concrete bridge FEM assessment.

Table 1: Comparison of condition assessment techniques for concrete bridges

Technique	Description	Advantages & Limitations	
		Advantages	Limitations
Visual Inspection (VI)	Trained engineers have to recognize, register, and evaluate the physical condition of different bridge elements using inspection manuals and defined codes.	BMSs, rely primarily on VI to record components condition ratings, which are quantified and standardized through a priority-ranking procedure. It is the most cost-effective method	Subjective evaluation, results greatly depend on the qualification of persons conducting inspections. Considers only the observed physical health of the bridge.
Non-Destructive Evaluation (NDE)	Each NDE method uses a unique physical principal of the bridge materials to identify locations flaws or deterioration without damaging the elements.	Objectify the inspection process and make it more fast and reliable to provide effective, and accurate condition assessment.	No single NDT technology is capable of identifying all of the various deterioration phenomena. It requires trained persons for data collection, and interpretation.
Structure Health Monitoring (SHM)	Encompasses a range of methods and practices designed to capture structural response, and detect anomalous behavior.	Reliable and potentially real-time bridge assessment. Wireless sensors alleviated the cost associated with cabled monitoring systems. More meaningful than using loading response data.	Requires routine, on-site maintenance. Wireless sensors often rely on battery power. The complexity and size of the bridge could result in complex SHM system.

The bridge deterioration process exhibits the complex phenomena of physical and chemical changes that occur in different bridge components. Each bridge element has its own unique deterioration rate which is directly related to the design and construction techniques, maintenance practices, materials properties and the operating environment. The advantages and limitations of the deterioration models are summarized in Table 2. Deterministic models are the simplest models where the deterioration rate of one element is generalized to all similar elements. The main limitations of these models are the failing to consider uncertainty and ignoring the effect of unobserved variables and hence, the inherent stochastic nature of demands. Several advantages for stochastic models include: (1) represent uncertainty in initial condition, assessment errors and deterioration process, (2) provide an unbiased estimate of needs within any time frame, and (3) do not require long time-series of data. However, they still suffer from several limitations: (1) future deterioration depends only on the current or preceding condition state and does not relate to the historical condition of a bridge or any other attribute (e.g. maintenance) of the bridge elements, (2) assume discrete transition time intervals, a constant bridge population, and stationary transition probabilities, and (3) transition probabilities are estimated in terms of subjective engineering judgement and require frequent updating. Mechanistic models embrace a reliability-based approach and focus on relevant failure modes of the bridge in determining the reliability of the bridge over time. These models relate the qualitative measurement of the condition state to the quantitative physical parameters of the bridge such as material properties, stress conditions, structural behaviors, which are critical data for assessing the structural capacity of the bridge. Although, these models have the ability to predict the deterioration with high accuracy and efficiency, none of the transportation agencies incorporate them in their BMSs as it is difficult to consider the various variables affecting the deterioration process. Another key limitation to this approach is the associated cost to perform detailed condition survey for the network level analysis.

Table 2: Comparison of deterioration model techniques for concrete bridges

Technique	Description	Advantages & Limitations	
		Advantages	Limitations
Deterministic Models	Use a single, defined value to describe bridge element conditions at a certain given time. Use historical data to estimate the deterioration rate.	Simple and easy to understand and develop. Require only one condition rating after construction.	Assume that the environment, structure system, and material properties exhibit the same behaviour. Not accurate for long-term prediction.
Stochastic Models	Consider discrete condition states identified for inspections. Describe the probabilities of all variables by a probability distribution function.	Consider the inherent uncertainty and randomness involved in the deterioration process. Can predict condition within any time frame. Require only two cycles of inspection.	Condition distribution is independent of the past conditions or any other attribute. Assume discrete transition time intervals. Subjective transition probabilities.
Mechanistic Models	Use quantitative performance indicators of the damaged elements through detailed condition surveys and analytical assessments.	Can accurately predict the initiation, propagation, and failure induced by different damage mechanisms, such as corrosion, fatigue, and overstress.	Difficult to develop when multiple types of deterioration processes are to be modeled together. Costly for data collection, analysis, and modeling.

The decision of which technique is more appropriate for bridge condition assessment and deterioration modeling is highly dependent on the nature of the available data and is driven by certain factors: (a) the mechanism of deterioration in the bridge being investigated, (b) expected output from the evaluation method, (c) how the assessment data will be used, and (d) level of complexity and available time to conduct the evaluation. For instance, corrosion can be tracked by monitoring the electrical outputs in a cathodic protection system, whereas scour monitoring involves using acoustic, pier-mounted sensors to directly track scour depth in the regions of bridge piers and abutments. Cameras are useful for displacement monitoring, whereas strain gauges are suitable for deformations. For bridge decks, if delamination is of greatest concern, IRT or IE with a higher degree of automation are appropriate, while GPR is suitable if corrosion of greatest concern.

6. CONCLUDING REMARKS

Bridge engineering is rapidly evolving and much work is ongoing in the specific matter of bridge assessment and deterioration modeling. The present review demonstrates clear need to upgrade existing BMSs to incorporate recent research in this field. The following concluding remarks were drawn from the present study: (1) NDE and SHM systems play a major role in effectively managing bridge infrastructure. They can also enhance the numerical modeling of deterioration prediction. However, applying such methodologies requires cost-benefit analysis in both the short- and long-term; (2) at present, NDE methods, such as GPR, IE, and IRT are being commonly used for quantitative evaluation of bridge condition to augment visual inspection data; (3) most current research efforts aimed at verifying the capability of integrating NDE techniques to have an objective deterioration system; (4) The Markovian and regression models have restrictive assumptions implicit in their respective formulations; and (5) fully automated data collection and interpretation analysis seems to be the primary need to improve current BMSs.

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